

Hyperloop Commercial Feasibility Analysis:

High Level Overview

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List of Abbreviations

Abbreviation	Term
CAHSR	California High Speed Rail
HSR	High Speed Rail
HT	Hyperloop Technologies, now rebranded as “Hyperloop One”
HTT	Hyperloop Transportation Technologies
ROW	Right of Way

Executive Summary

Hyperloop is a concept for very high-speed, fixed-guideway, intercity surface transportation, using capsule-like vehicles that operate in sealed partial-vacuum tubes. At this stage, the technology is unproven, but it has elicited a great deal of interest from journalists, investors, engineering firms, and governments. This research is being conducted to provide a high-level evaluation of hyperloop in terms of its commercial potential, environmental impact, costs, safety issues, and regulatory and policy issues and to identify further research topics related to the technology. This research is intended to provide NASA decision-makers with appropriate context to make decisions on the future direction of NASA's involvement in Hyperloop research.

Commercial Potential-Passenger

The hyperloop technology is touted as having very fast speeds, faster than existing forms of passenger travel, and as being able to provide that service at lower cost than high speed rail (HSR). Hyperloop's proposed speeds (maximum 720 – 760 mph and average of 600 mph) would indeed be faster than air, maglev, and HSR. For a trip between San Francisco and Los Angeles of roughly 400 miles, the resulting time savings over air or maglev would be about 45 minutes. However, all three modes would likely have stations that terminate at the outskirts of the major city and thus require additional time on local transit for travelers to reach their final destination. The time savings over HSR is more substantial at 2 hours, but HSR stations are generally found downtown which provides savings in access and egress time.

It is not clear whether hyperloop's very high speeds would be comfortable for passengers. Because it is a fixed guideway the route needs to be planned with exacting precision so that passengers are not subject to uncomfortable g-forces on curves or dips. In contrast, passengers find maglev and HSR trains very comfortable and appreciate being able to use their time productively.

Proponents claim that because the system is enclosed in a tube, it will be impervious to weather delays. However, maglev is also resilient to weather because the train is elevated above the guideway it can operate in bad weather. HSR, while not impervious to bad weather, is considerably more resilient than air.

As originally described, hyperloop capacity would be far lower than HSR. However, that capacity could potentially be increased by using larger pods or by having more tubes stacked on a single pylon structure.

Hyperloop appears to be able to offer faster speeds than other modes of passenger transport, but other modes offer advantages in other dimensions such as proximity to downtown areas and/or passenger comfort. Much of the public is not aware of the higher speeds offered by maglev technology, likely because it has only been deployed in one instance, in Shanghai, China. However, that one deployment has shown that it is feasible and thus it would be a less risky investment than the entirely unproven hyperloop technology.

Commercial Potential-Freight

The early discussions related to hyperloop technology focused on its potential for passenger transport, but more recent discussions of hyperloop have focused on freight. This shift in focus to cargo is perhaps because of the (likely accurate) perception that it will be less risky to prove the technology on cargo than on passengers. The portion of the freight market that might be interested in the high speeds offered by hyperloop would likely be the current market for air freight which accounts for just 2 percent of ton miles, but represents 40 percent of freight value. However, aircraft serve this market through vast hub-and-spoke networks that accumulates freight from many origins and distributes them to many destinations. It would take a massive investment in a hyperloop network to create the same coverage and the value of incremental time savings over air would likely be small.

Because only air (expensive but fast) and ship (cheap but slow) are available for cargo shipment across water or distance that prohibits building a bridge, there is a compelling need for an additional mode. For cargo, the super-fast speeds are not of themselves the compelling feature of hyperloop, rather super-fast speeds enable higher throughput for a given tube size.

Recent presentations by Hyperloop Technologies (HT)¹ have focused on putting the hyperloop tubes underwater as a way to avoid land acquisition costs for right of way. The HT presentations also mention the idea of using hyperloop to facilitate off-shore port facilities. Many ports are capacity constrained and unloading containers from ships to a hyperloop tube to be brought inland for sorting and distribution using equipment on offshore platforms could provide much needed expansion for port facilities.

Environmental Impact

The various hyperloop proponents make much of the idea that hyperloop would be completely powered by solar technology. While that is certainly not true of air travel, both maglev and HSR are electrically powered and could be powered by solar if desired. It is not clear how much energy would be needed to operate hyperloop but an HT presentation stated that most routes would be two to three times more energy efficient than air travel per passenger mile. Maglev and HSR are also two to three times more energy efficient than air, so that criteria does not seem to favor hyperloop over existing high speed transportation options.

Discussions of environmental impact tend to focus on emissions during operations and ignore the full lifecycle emissions during manufacture of the equipment during construction of the guideway. Those impacts would be present for any new transportation project but at this point the information is not available to compare across alternative transportation modes.

¹ Hyperloop Technologies has recently rebranded themselves as Hyperloop One.

Costs

There is not much detailed information available about the costs of hyperloop. The most detailed information came from the “Hyperloop Alpha” white paper written by Elon Musk which provided an estimate of \$17 million per mile. Subsequent to the Alpha white paper, HT gave a presentation citing \$25 -\$27 million per mile for just the technology, excluding land acquisition. For an almost entirely underwater track specifically from Helsinki to Stockholm HT estimates a cost of \$64 million per mile including vehicles.² For an approximate frame of reference, California HSR faces costs of \$63-\$65 million per mile and in Europe the cost is \$43 million per mile, although those figures include costs of land acquisition but exclude train sets. Thus, cost estimates for a land-based hyperloop system may appear lower than other modes, but as the technology is still conceptual and in very initial testing, there is uncertainty in both the underlying infrastructure needed to operate a system and the cost to construct it. One issue driving the idea that hyperloop would be lower cost to build than HSR is that by constructing an elevated system on pylons, the builder would just need to purchase “air rights” which would be lower cost than outright land acquisition. Further, there is an assumption that the system could operate on the existing highway right-of-way further reducing costs. In addition, there appears to be an understanding that the tube guideway would be lighter weight than a steel wheel rail system and thus be cheaper to build. HSR and maglev could also be built on elevated tracks and on existing highway right-of-way. However, the relative cost savings from building a supposedly lighter-weight elevated system is an interesting future research question. Air appears to have a cost advantage because outside of airport facilities, no right of way is needed.

Regulatory and Policy Issues

At low fares (for example, \$20 for Los Angeles to San Francisco) and relatively low capacity (pods carry 28 passengers and one tube in each direction), the hyperloop would not be able to cover its construction costs. Thus, a public entity of some sort would need to subsidize the endeavor. A Hyperloop Transportation Technologies (HTT) executive has said as much. At present, there appears to be a general presumption against government interfering in the private marketplace or placing large “bets” on particular new technologies or products, at least in the US. For that reason, the various hyperloop companies appear to be focusing on foreign markets.

Government officials (foreign or domestic) would need to consider whether the public interest is best served by using public right of way for hyperloop. It is an open question as to whether communities would be willing to host a facility that services long distance travel mode at the expense of using resources to provide local transit.

Safety Issues

² <https://hyperloop-one.com/blog/FS-Links-Hyperloop-One-Baltic-Sweden-Finland-Aland-Islands>

A completely new transportation mode needs to not only address safety issues that are known from existing modes but also anticipate any safety issues specific to it. The following issues have been identified and the companies that are developing the hyperloop technology are certainly aware of them. The proposed solutions would need to be carefully tested and vetted.

- How will tube construction allow for emergencies, such as rapid depressurization or large-scale leaks, capsule malfunction, or natural disasters such as earthquakes?
- What will happen in the event of the depressurization of a Hyperloop capsule?
- What happens if a capsule is stranded in the tube? Where will the emergency exits be?
- How fast can the capsule decelerate for emergency stop without damaging the system?
- What is the capsule behavior if it hits higher or even normal density air while traveling at 700 MPH? Can it be designed to survive that and protect the passengers? How fast will the capsule decelerate if it encounters high-density air?
- Can the problem of excessive drag on the capsules be overcome even in such a thin atmospheric environment? What is the potential of supersonic air surrounding the capsules?
- If there is a large tube breach, will the air be filling the tube at a high velocity? Will the additional speed and turbulence increase the danger to the capsule? Will oxygen masks work in a major capsule breach?
- How long will the system continue to run if power is lost in the area?
- Is it possible to provide a fire suppression system inside the capsule?
- What material and method of tube construction presents the ideal combination of safety, cost, and overall function (e.g., steel, carbon fiber, Kevlar)?

Key Research Questions

1. Is the hyperloop transportation system sufficiently lightweight that there would significant construction cost savings compared to building an elevated HSR or maglev system?
2. What are the technology hurdles to building hyperloop underwater and can they be overcome?
3. Can the capacity of a hyperloop pod be expanded to seat more than the originally proposed 28 passengers?
4. What would be the weight limit for a freight capsule?
5. How big would the tube need to be in order to carry a standard size shipping container?
6. Can the system be designed so that in addition to carrying long distance passengers, it can also provide local transit service?
7. Would hyperloop be loud for passengers? Would hyperloop be loud in communities?

I. Introduction

Hyperloop, as described conceptually by Elon Musk of SpaceX and Tesla in an August 2013 white paper, is a new, very high speed, intercity transportation mode. It consists of two (or more) very long tubes, elevated on pylons, which have been partially evacuated of their air, creating a partial vacuum. Linear induction motors propel small passenger or freight capsules riding on low-friction air bearings at very high speed within the tubes. The partial vacuum dramatically lowers aerodynamic drag resistance, which is ordinarily a key limitation on vehicle speed. Arrays of solar panels along the guideway would provide much or all of the required electrical power, with claims of very low overall power consumption per passenger-mile. Proposals include 28 passenger pods, passenger pods that also carry up to three vehicles, and freight pods that can hold a standard 40 foot long shipping container.

This report provide a high-level evaluation of hyperloop in terms of its commercial potential, environmental impact, costs, safety issues, and regulatory issues and to identify hurdles to its commercial and/or operational feasibility. This research is intended to provide NASA decision-makers with appropriate context to make decisions on the future direction of NASA's involvement in Hyperloop research.

Mr. Musk has described the concept as an "open-source platform," making his conceptual white paper available to others to refine the design. SpaceX has announced plans to build a one-mile test track at its headquarters in Hawthorne, California. It also was one of the sponsors of Hyperloop pod design competition held at Texas A&M in January 2016. At the design competition, US Secretary of Transportation Anthony Foxx called Hyperloop a "very solid idea" that merited further beta testing, and that the federal government had a "responsibility" to support the idea.

Hyperloop Technologies, Inc. (HT) is a venture capital-funded company currently hiring engineers and developers. The firm has recently rebranded itself as "Hyperloop-One" but this report will continue to refer to the entity as "HT." Their initial focus appears to be on freight and they are based in Los Angeles, California. The firm appears to have informal ties to Space X and Tesla. The firm conducted a propulsion test in May 2016.

Hyperloop Transportation Technologies (HTT) is using a crowdsourcing model, in which 100 core technical researchers work part-time for equity in the company. They have announced plans to construct a five-mile, demonstration test track along Interstate I-5 in Quay Valley, California, a privately-owned planned community.

Transpod is a Canadian start-up with plans to implement Mr. Musk's hyperloop idea.

The sources used for this report include the white paper by Mr. Musk titled "Hyperloop Alpha,³" HTT's

³ http://www.spacex.com/sites/spacex/files/hyperloop_alpha-20130812.pdf

“Official Crowdstorm Documentation,” HT’s website (now www.hyperloop-one.com), two presentations made by Vice President of Technology and Development at HT,⁴ and press articles.

“Hyperloop Alpha” focuses on Hyperloop connecting San Francisco and Los Angeles using the I-5 right-of-way. HT states that they are focusing on freight initially but if they were to build a passenger system connecting San Francisco and Los Angeles, they would chose an underwater route for the tube. HTT identified several potential markets for HL service.

⁴ November 2015 at KTH in Sweden accessed at <https://www.youtube.com/watch?v=1BiCFFXWgzE&feature=youtu.be&t=634>; January 2016 at Purdue accessed at https://www.youtube.com/watch?v=w7QXUiJY_jI.

2. Passenger Service

2.1 Hyperloop Comparisons to Other Modes

A passenger transportation option can be analyzed in terms of its service characteristics and operational features. Service characteristics experienced by travelers include: travel time, frequency, user cost, comfort, and reliability. Operational features include: energy consumption, capacity, system resilience, and system interoperability. Capital costs and operating costs are discussed in Chapter 4. These features of hyperloop are described below. In subsequent sections, hyperloop is compared to other high speed modes along these service characteristics. The important results of the comparison to other modes is that hyperloop is not categorically better than other existing modes. In fact, it is very similar to other fixed guideway systems. Although it provides marginally higher speeds, the costs of attaining those speeds are uncertain while proven technologies are available that achieve almost those same attributes.

2.1.1 Travel Time

Travel time is comprised of three components: line haul time, station time, and access/egress time. Line haul time depends on the speed of the technology and any ramp-up/ramp-down, taxiing time including tarmac delay (for air travel), station dwell time and intermediate stops (for rail or maglev travel). Station time refers to the time needed at the embarking/disembarking station for things like ticketing, security screening, baggage loading, etc. In the case of very frequent non-scheduled service such as subways, travel time includes the expected wait time between trains usually estimated as one-half the headway between trains. Access and egress time depend on the spatial relationship between the station and the ultimate origins and destinations of the individual travelers.

Hyperloop is estimated to have maximum operating speeds in the range of 720-760 mph over distances of 300 - 500 miles. Those top speeds are mitigated somewhat by the need for gradual acceleration or deceleration and at the beginning and end of the trip. "Hyperloop Alpha" describes hyperloop capsules making the trip from the San Francisco Bay area to the Los Angeles area in roughly 35 minutes, with no intermediate stops. This is a distance of about 350 miles for an average speed of roughly 600 mph. However, there would be no taxiing time as with air travel or time spent at intermediate stops as there is for rail or maglev.

Of course, line haul time is just one component of total travel time. There is also the time needed to access and egress the station to the ultimate origin and destination. The amount of access and egress time needed will depend on where the hyperloop terminals are located. Downtown locations provide time savings for passengers but higher costs associated with land acquisition along with other institutional barriers related to building in areas of high population density.

As regards station time, at this point it is not clear whether hyperloop would require TSA-style security

screens as is currently done for air travel. On the one hand, TSA-style screening is not currently required for rail travel in the US, Europe, or China and the scope for damage is confined to the system itself unlike air travel where the planes can be diverted to other destinations in the case of hijackings and become weaponized such as what occurred on 9/11. On the other hand, hyperloop would be high profile asset and as such might attract attention of potential terrorists and thus warrant special protective measures. In fact, "Hyperloop Alpha" states that the system would indeed be subject to TSA style screenings. It might be possible that the government would not require security screenings as a public safety measure but instead the owner (a corporation or a public agency) of the asset might require screenings as a means of protecting its asset. Baggage handling for hyperloop is anticipated to be similar to that of air, where luggage is stowed in a separate portion of the vehicle and thus requires special handling. Rail and maglev riders generally handle their own luggage which saves time at the station.

The table below compares these travel time characteristics among high speed modes. The hyperloop technology claims the highest maximum and average speeds, more than twice as fast as the next fastest modes, air and maglev, over an intermediate range of less than 500 miles. For markets like LA to SF and LA to Las Vegas, those speeds translate to 45 minute savings over air. That time savings over air may be even greater if hyperloop does not require TSA-style security screening, although that issue is not clear; HTT documents say TSA-style screening would not be necessary while Alpha and HT say that TSA-style screening would be necessary. Maglev also does not require security screenings and would face similar hurdles to having stations located downtown because it also is new mode. HSR for the LA to SF market is planning travel times of 2 hours and 40 minutes which would be 2 hours longer than a hyperloop trip, but HSR does not require TSA-style screenings and has stations located in the downtown areas which would provide travel time savings for access/egress portions of the trip. Air travel experiences very high boarding time as passengers must all squeeze through one access point (a bottleneck). Maglev and HSR allow for fast boarding through multiple boarding points along trainset and wide aisles allow for passenger to pass others. Hyperloop is anticipated to offer similarly fast boarding times by using rollercoaster type seating procedures.

Table 1. Travel Time Comparisons

	Hyperloop	Air	Maglev	HSR
Maximum Speed	720 mph (HTT) 750 mph (HT) 760 mph (Alpha)	515 mph (basic cruise speed of CRJ700)	375 mph (Japan Railway test track) ⁵	150 mph (Acela, Boston to NYC) 168 mph (TGV Paris to Lyon) 200 mph (Tōhoku Shinkansen) 220 mph (CAHSR)
Average Speed⁶	600 mph (Alpha, SF to LA)	253 mph (SF to LA) ⁷	143 mph (Shanghai Maglev, 19 mile line) 265 mph (proposed Tokyo Nagoya line)	70 mph (Acela, Boston to Washington) 102 mph (Acela, Boston to Providence) 130 mph (TGV Paris to Lyon) 164 mph (CAHSR)
Representative Travel Times				
LA-LV (270 highway miles)	26 minutes (HTT)	70 min	61 min (imputed at 265 mph)	84 min (DesertXpress, 186 miles from Victorville to LV – plus 85 miles Victorville to LA)
SF to LA (382 highway miles)	35 minutes (HTT)	83 min	86 min (imputed at 265 mph)	160 min (CAHSR)

⁵ <http://www.cnn.com/2015/04/21/asia/japan-maglev-train-world-record/>

⁶ Distance divided by Station-to-Station or Airport-to-Airport travel time (includes allowances for curves, station stopping patterns, etc.)

⁷ Calculated as distance divided by ramp to ramp travel time.

	Hyperloop	Air	Maglev	HSR
Access/Egress Time	Low if stations are downtown Similar to air if stations on outskirts	Generally high	Low if stations are downtown. Shanghai Maglev requires another 20 minutes by subway.	Low - stations are generally downtown-
Station Time for Security Screening	Low, no security screening (HTT) Same as air, need TSA-style screening (Alpha & HT)	High - requires security screening	Low - no security screening	Low - no security screening
Station Time for Baggage Handling	High (similar to air)	High	Low	Low
Station Time for Passenger Loading	Potentially low, envision roller coaster like seating procedure	Highest of all modes, as all passengers enter through one point, causing bottleneck	Multiple boarding points along trainset allow for fast boarding	Multiple boarding points along trainset allow for fast boarding

2.1.2 Frequency

“Hyperloop Alpha” envisions Hyperloop departures every 2 minutes on average, or as frequently as every 30 seconds during peak periods meaning that in theory wait time should be very small. However, that assumes that supply and demand are evenly balanced temporally. That is, that passengers arrive at a rate equal to the availability of pods. If more passengers arrive than there is pod capacity, queues will form and station time will increase. The discussion of hyperloop discusses the high frequency as being an advantage because the proponents claim there will always be a new pod, if you miss the first pod. The ability to provide “walk-up” service is business plan decision. Airlines could provide similar walk-up service but have found it more profitable to use advance ticket sales and yield management techniques to charge only very high prices for walk-up service. Current Amtrak service operates similarly in that a limited number of low priced tickets are available which rewards those who book tickets early. Walkup

service is available but at higher prices, although the price increases are not as substantial as they are in air travel. But those are business plan features, not features of the technology.

Hyperloop provides much higher frequency than other modes. However, for intercity travel, frequencies higher than 4 per hour tend not to provide additional utility to riders other than providing additional capacity. That is, the amount of reduced wait time (estimated as one-half of headway, or 7.5 minutes for 4 departures per hour) is perceived as not significant for a longer distance trip. California HSR has plans for 12 departures per hour or 5 minute headways which would probably be perceived as being only slightly less preferred than hyperloop's 30 second headways. A direct comparison to air in terms of frequency is not easy since air tickets are generally purchased in advance for a specific boarding time. However, for major markets multiple carriers generally offer hourly service to accommodate a variety of passenger scheduling needs.

Table 2. Frequency Comparisons

	Hyperloop	Air	Maglev	HSR
Frequency	30 – 120 per hour 30 sec to 2 minute headways	3 per hour (LA-SF)	4 per hour (Shanghai) 15 minute headway	12 per hour 5 min headway (CAHSR)

2.1.3 User Cost

"Hyperloop Alpha" suggests fares of \$20 for the San Francisco the Los Angeles route which would apparently be used to cover operating expenses. However, this research has not found any sources providing estimates of operating costs for the system. A presentation made by an HT executive cited \$10 to \$15 for a route linking Abu Dhabi to Dubai. However, that presentation seemed to indicate that that fare amount was a price point which the market could bear, rather than an estimate of the service's operating cost. In a pricing structure where fares are only used to cover operating costs, some entity would be required to fund the upfront capital construction and vehicle costs without repayment. An assumption of public funding can only be speculative, especially in the current constrained fiscal environment for government expenditures.

Table 3. Fare Comparisons

	Hyperloop	Air	Maglev	HSR
Fares (per mile)			\$0.33 per mile (Shanghai)	\$0.20 per mile (CAHSR) \$0.25 per mile (Italy) \$0.22 per mile (China) \$0.52 per mile (Paris Lyon) \$0.50 per mile (Acela)
LA-LV		\$50 (Desert Express)		
LA-SF	\$20 but does not cover projected costs (Alpha)	\$68-\$200 depending on when purchased	\$0.33 per mile	\$86 (CAHSR)
Abu Dhabi-Dubai	\$10 - \$15			

2.1.4 Comfort

Many news articles express concern about passenger comfort while traveling at such high speeds, even calling hyperloop a “vomit comet.” This is because at high speeds hills or curves will exert g-forces on passengers. A commonly cited metric in articles discussing hyperloop is that 0.5g is the maximum for human comfort. To achieve that speeds, must be lowered, pylons must create flat or only gradual rises, and/or the route must use only very wide turns. While 0.5g is cited as a general measure of tolerance, there is variability among individuals about what they can personally tolerate. Thus, one could expect that some portion of the traveling public would find the 0.5 g threshold uncomfortable and avoid the technology. A study conducted by the Volpe Center published in 1994 finds lower thresholds 0.3 g for positive vertical acceleration and 0.2g for negative vertical acceleration using acceptability criteria that 95 percent of passengers would not hesitate to ride again. In one presentation an HT executive mentions similar tolerances, so it appears that HT is aware of the issue. In turning maneuvers, Volpe study found that this criteria was achieved when roll rates were less than 7 degrees per second and bank angles were less than 37 degrees.⁸ It is not clear if any of the hyperloop firms are planning routes using those parameters.

There are also concerns about noise for the occupants. Mention has also been made of lack of restrooms in a hyperloop pod but for trips on less than an hour, this should not be a problem for most of

⁸Sussman, E. Donald, J. K. Pollard, P. Mengert, and R. DiSario. *Study to establish ride comfort criteria for high speed magnetically levitated transportation systems*. No. DOT-VNTSC-FRA-94-1. 1994.

the traveling public.

Passengers tend to rate HSR and (by inference maglev) as being quite comfortable with sufficient leg room, ability to walk around, and work productively. Air travel is commonly the target of complaints about those issues.

Table 4. Comfort Comparisons

	Hyperloop	Air	Maglev	HSR
Passenger comfort	Unknown, “Vomit Comet” Potentially noisy	Less leg room, less productive time use	Unknown for long distances but likely similar to HSR	Comfortable and able to use time productively

2.1.5 Reliability

One advantage of hyperloop touted by its supporters is resilience to weather conditions which can plague air travel and to a lesser extent rail travel. Maglev, because of it is suspended above its guideway is also considered to be resilient to weather conditions as well. HSR and even conventional rail are more resilient to weather conditions than air travel.

Table 5. Reliability Comparisons

	Hyperloop	Air	Maglev	HSR
Reliability	Protected from rain and snow	Most affected by weather events.	Can operate in all weather conditions because it is separated from guideway	Affected by ice and snow events, but more resilient than air. Even conventional rail carries additional passengers when weather affects air travel.

2.1.6 Energy consumption

“Hyperloop Alpha” emphasizes that the hyperloop technology will be completely solar powered. However, maglev and HSR are also electric and could in theory also be solar powered. Focusing on the amount of energy required, HT found that for most routes hyperloop would be 2 to 3 times more energy efficient than air on a passenger mile basis; however, maglev and HSR also use 1/3 the energy of air on a passenger mile basis. The emphasis on solar power tends to obscure the fact that no technology is entirely clean because there is energy consumed in manufacture and construction of the technology.

Table 6. Energy Consumption Comparisons

	Hyperloop	Air	Maglev	HSR
Fuel	Electric	Jet Fuel	Electric	Electric
Power Source	Solar powered with backup batteries		Grid, so mix of all energy sources in region. There is no reason maglev couldn't be solar powered as well.	100% renewables via purchase of offsets (CAHSR) Grid, so mix of all energy sources in region. There is no reason HSR couldn't be solar powered as well.
Energy Consumption (BTUs per Passenger Mile)	Short route: 5-6x more fuel efficient than air Other routes: 2-3x more fuel efficient than rail ⁹	3,230 BTU/p-m	1,180 BTU/p-m ¹⁰	975 BTU/p-m ¹¹
Emissions-Operating Phase	Zero	High, but improving over time ¹²	Depends on Electric Source	Depends on Electric Source
Emissions-Construction Phase	Not zero due to manufacturing of tube and vehicles	Additional due to manufacturing of vehicles and construction of airport facilities	Additional due to manufacturing of guideway and vehicles	Additional due to manufacturing of guideway and vehicles

⁹ <https://www.youtube.com/watch?v=1BiCFFXWgzE&feature=youtu.be&t=2989>

¹⁰ “Japan commits to world’s longest maglev train system,” Electric Vehicle World, 26 Feb 2013 accessed at <http://evworld.com/focus.cfm?cid=122>

¹¹ Bay Area to Central Valley HST Final Program EIR/EIS, Table 3.5-5 accessed at http://www.hsr.ca.gov/docs/programs/bay_area_eir/BayCValley_EIR2008_Vol1Ch3_5energy.pdf,.

¹² New ICAO standards for CO2 emissions for jets are being adopted that will reduce emissions and fuel use by 20 to 25 percent for newly manufactured large jets.

2.1.7 Capacity

As mentioned above, “Hyperloop Alpha” envisions Hyperloop departures every 2 minutes on average, or as frequently as every 30 seconds during peak periods with pods capacity of 28 people. Taken together those two parameters suggest a maximum capacity of 3,360 passengers per hour. As will be discussed further below, this capacity is considerably lower than other high-speed modes and has important consequences for financial viability as transportation is an industry that generally exhibits significant economies of scale. However, it appears possible that the pods could be made longer to accommodate more passengers. Also, multiple tubes could be constructed on the same pylon structure to increase capacity.

Table 7. Capacity Comparisons

	Hyperloop	Air	Maglev	HSR
Capacity – Passengers per vehicle	28 per vehicle (this may be flexible)	130 per plane (LA-SF) 10,000 per hour LAX total	574 per train 436 per train (Tokyo-Nagoya)	1,000 per train (CAHSR)
Capacity - Passengers per hour	840 – 3,360 per hour	400 per hour (LA-SF, average current schedules)	2,296 per hour (Shanghai, 4 trains per hour)	12,000 per hour
Passengers per year	15 million per year (maximum capacity)		Unknown	28 million per year (forecast CA HSR) 140 million per year (actual, Tokyo-Osaka)

2.1.8 System Resilience

Repairs within a tube will necessarily halt operations in that tube and depending on system redundancy may impact other tubes. Repairs may potentially require the pressurization of the tube for workers to operate. If the repairs are external, operations may still need to be halted to prevent any external disturbance to operations and the tube’s exacting tolerances. Halting operations in one direction may halt operations in the opposite to prevent the stacking of capsules in the system depending on the capacity of a capsule maintenance and inspection facility (stations are described to have a capacity of only 3 to 4 capsules). In a presentation, HT made a comment that they will use 3 tubes to address the

issue of maintenance. In contrast, rail and maglev systems allow for switching between tracks for track maintenance. Air travel does not require maintenance of way. For maintenance and repair of vehicles, all the modes share the ability to take a single vehicle out of service and replace it with others but because the service involves many small pods, taking one out of service will have less impact on operations than taking one of a limited number of trainsets out of service for maintenance.

There is question of how difficult it will be to maintain the partial vacuum in the tube over long distances. Will minor shifting of pylons result in significant impacts on operations? Will passengers feel jolts and bumps if pylons shift?

Table 8. System Resilience Comparisons

	Hyperloop	Air	Maglev	HSR
Resiliency	<p>Unless multiple tubes are stacked in each direction, maintenance or repair in one section of tube would require entire route to shut down. An HT presentation mentions building 3 tubes.</p> <p>It's unknown how minor shifts of pylons might impact operations.</p>	<p>Aircraft can be replaced to keep service going during maintenance.</p>	<p>Because the train is elevated, the guideway experiences minimal wear and tear, compared to rail</p> <p>Maglev can switch between rails, to allow for maintenance.</p>	<p>Multiple tracks and sidings allow system to continue operations even while maintenance is performed</p>

2.1.9 System Interoperability

Because it operates in such a unique environment, hyperloop would be able to provide interoperability with other modes. This problem has plagued adoption of maglev as well. However, HSR provide interoperability with conventional rail so that those modes can share right of way. This is particularly advantageous in cities where land acquisition costs are high. Further, communities are less likely to accommodate a large infrastructure project that doesn't provide benefits to the people in the host communities. But a community would probably be more welcoming of a new HSR track if that track could also provide local transit service.

Table 9. System Interoperability Comparisons

	Hyperloop	Air	Maglev	HSR
System Interoperability	Not interoperable, cannot provide local transit	Not interoperable, cannot provide local transit	Not Interoperable, but can provide short distance and long distance trips on same track.	HSR track and stations can also be used by conventional intercity rail and local commuter rail, and can provide short distance and long distance trips

2.1.10 Automation

Hyperloop would be completely automated with no pilot, driver, or engineer. Discussion of hyperloop often discuss the safety benefits that are expected to result from the removal of human error from the transport system. Automation is being added incrementally to the other modes with features of positive train control (rail), auto pilot (aviation), and speed regulators (trucking). The Shanghai Maglev does have a driver, but some driverless people-mover transit systems exist. It is only speculation as to whether complete automation will be safer than using human drivers.

2.1.11 Enclosed System

The fact that hyperloop would a completely enclosed system that is protected from interactions with the natural world (trees falling over rail tracks, birds sucked into jet engines, etc.) and from transportation modes (rail grade crossing with highways) would likely also provide safety and reliability advantages to hyperloop.

2.2 Markets

“Hyperloop Alpha” states that hyperloop is appropriate for markets of 900 miles or less. However, it may be more realistic to focus on markets 200-500 miles apart. At longer distances, the construction costs of the guideway begin to erode any cost-effectiveness advantage over aviation; for shorter trips, there is little net time savings over the automobile due to the need to access a terminal and go through check-in procedures.

HTT Crowdsource suggest several markets. The top markets identified in the paper are the following:

Los Angeles to San Francisco. Hyperloop would be competing with California HSR which is already under

construction and for which the California government has already made substantial investments. It is unlikely that the State would allow access to the I-5 corridor for hyperloop, given that doing so would undermine its own investment.

Los Angeles to Las Vegas. There is currently no passenger rail service to downtown Las Vegas so that may make it an attractive market for hyperloop because of lack of competition. DesertXpress is project for HSR between Victorville, CA and Las Vegas. Victorville is the starting point because of prohibitive cost of going through Cajon Pass. The estimated cost is \$5 to \$6 billion. Of that, approximately \$1 billion is from private financing. The project applied for federal loan for remainder was not willing to accept Buy America provisions related to federal funding. So no further progress has been on the proposal. The same challenges faced DesertXpress (cost of crossing Cajon Pass and lack of federal funding) would likely affect hyperloop as well.

Texas Triangle. This currently has no real rail service so it may be a good market for hyperloop due to the presence of several large cities and no competitive rail service. However, there are current plans for a privately financed HSR line between Dallas/Ft. Worth and Houston with travel times of less than 90 minutes for the 240 mile trip. (texascentral.com). Below are the travel times HTT estimates for hyperloop:

- Dallas to Houston 22.9 minutes
- Dallas - Austin - San Antonio HL 28.6 minutes
- Houston to San Antonio 19.6 minutes

Northeast Corridor. The NEC already has a mature rail market and HSR in the form of the Acela Service. The NEC Future project (NECFUTURE.com) is a large planning effort to improve the NEC rail service. The costs of acquiring ROW in this region will be extremely high due to high land prices. The topology would require many large bridges and tunneling for urban areas. Coordination among several states is also challenging. Below are the travel times HTT estimates for hyperloop:

- New York – Philadelphia
- New York – Boston 19.5 minutes
- New York – Washington 21 minutes

Vienna, Austria - Bratislava, Slovakia - Budapest, Hungary. It currently takes 1 hour to get to Bratislava from Vienna by train or bus, HTT estimates it would take 8 minutes with hyperloop. It would take 10 minutes from Bratislava to Budapest by hyperloop. HTT has signed an Agreement with the Slovakian government to pursue the project.

Commuter Markets. Linking a city with an existing transit network and low housing costs but perhaps few employment opportunities to a city with high housing prices and abundant jobs would perhaps be the ideal application of a high speed, low cost service. However, any expensive transport link needs to serve a large number of travelers, which means high-density cities on each end which tend to have high land prices. However, some cases may exist, especially where natural or political barriers exist. One

example is the Oresund link connects Denmark and Sweden with 7.5 miles of tunnel and bridge. Apparently Danes buy homes in Sweden to take advantage of lower housing prices in Malmö and commute to work in Denmark. A Detroit to Chicago linkage might be a case of city pair with differing costs of living. However, the transportation link could probably be achieved with high quality rail service. The following are examples of potential commuter markets for hyperloop.

- **Gulf of Finland Tunnel.** The proposed tunnel would link Helsinki, Finland and Tallinn, Estonia across the Gulf of Finland. The cities are 31 miles apart. Rent in Tallinn is 50% lower than in Helsinki.¹³ HT is studying this city pair as a potential application of hyperloop.
- **Abu Dhabi to Dubai.** The two cities are 93 miles apart. Currently only personal auto, taxi, or buses are available to service the market. Rent in Abu Dhabi is only marginally lower than in Dubai.¹⁴ HT has indicated that they are exploring this city pair as a potential market for hyperloop.

2.3 Potential Revenues

“Hyperloop Alpha” states that a hyperloop trip between San Francisco and Los Angeles would cost the rider \$20 per one-way trip. With 15 million trips per year as the maximum capacity, that suggests \$300 million per year in farebox revenue. That calculation assumes average 2 departures per minute over all 24 hours. However, very few people would want to travel in the middle of the night. So that is an upper bound estimate. In addition, the Alpha white paper mentioned that the fares would cover operating costs which leaves one to wonder where the financing for the construction and development would come from. “Hyperloop Alpha” mentions billboards as an additional source of revenue but that would likely face public opposition. The HT COO, Bibop Gresta, states explicitly that government subsidies will be required.¹⁵

¹³ http://www.numbeo.com/cost-of-living/compare_cities.jsp?country1=Finland&city1=Helsinki&country2=Estonia&city2=Tallinn

¹⁴ http://www.numbeo.com/cost-of-living/compare_cities.jsp?country1=United+Arab+Emirates&city1=Abu+Dhabi&country2=United+Arab+Emirates&city2=Dubai

¹⁵ <https://theyoungbusinessmen.com/2015/12/07/our-exclusive-interview-with-coo-of-hyperloop-tech-bibop-gresta/>

3. Freight Service

3.1 Comparisons to Other Modes

While early discussions of the potential for hyperloop focused on passenger transport with freight as an afterthought, the more recent information provided by hyperloop companies focuses on freight. Such a development might perhaps be a natural extension of the current role pipelines playing moving certain types of gas and liquid goods such as oil, natural gas, and water.

This shift in focus to cargo is perhaps because of the (likely accurate) perception that it will be less risky to prove the technology on cargo than on passengers. When discussing hyperloop as freight mode there is a question as to the size limit and weight limit of a pod. There are some conceptual renderings that show the freight pod being large enough to accommodate a standard shipping container which is 10 feet by 10 feet by 40 feet. Given that NASA researchers found that the tube needs to be three to four times the size of the pod,¹⁶ this suggest a very large tub circumference (or a smaller specialized shipping container). Further there has been no discussion of what the tonnage limit for the pod would be. The tonnage limit would impact what type of freight could potentially be moved by hyperloop.



Figure 1. Cargo Pod Illustration

The existing modes of air, truck, and rail attract certain types of cargo and hyperloop does not offer clear advantages for the types of cargo carried by the existing air and surface modes. However, it may be an interesting prospect for movements over water where the existing shipping service is extremely slow.

¹⁶ Chin, J. C., Gray, J. S., Jones, S. M., and Berton, J. J. "Open-Source Conceptual Sizing Models for the Hyperloop Passenger Pod", 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA SciTech, (AIAA 2015-1587) <http://dx.doi.org/10.2514/6.2015-1587>

3.1.1 Air

The cargo currently served by air would be the most likely market for hyperloop service. However, air service has important operational features other than just speed.

Air service provides the fastest delivery times for long distance freight movements. The service is expensive and used just for time sensitive, high value, or perishable cargo. Air travel accounts for just 1-2 percent of all freight ton-miles, but 40 percent of freight value. Fast but expensive air service makes economic sense for high value cargo because having a high value cargo sitting unused while in transit imposes a cost. In economic terms it is called the time value of money and it can be estimated as the value of the freight times the days in transit times the daily cost of capital.

FedEx revolutionized package delivery with its overnight hub and spoke system. Although the internet has replaced the need for overnight letter delivery, overnight or two-day delivery has become very popular for e-retailers who must compete with brick-and-mortar stores who can provide products to customers instantly at point of sale.

Hyperloop is point-to-point, meaning there would need to be a high density of high-value, perishable, or time-sensitive freight moving between a specific origin and destination pair to support a hyperloop investment. Air networks like FedEx and UPS use a hub-and-spoke network to collect cargo from multiple origins, sort it, and then distribute it to multiple destinations. The flexibility of air (not having a fixed guideway) enables the hub-and-spoke system. Hyperloop would require enormous investment to create a similar hub-and-spoke system with the same geographic reach as the air network. As a result, air appears to be a better option for most the cargo that currently travels by air. There may be some niche markets where hyperloop would have an advantage, but data simply does not exist to pinpoint what those markets might be.

3.1.2 Truck

Hyperloop would be unlikely to take market share from truck. Using hyperloop would still require truck service at the origin and final destination which requires unloading from the truck and loading into the pod and then unloading from the pod and loading onto a truck for final delivery. Distances shorter than 500 miles (the suggested range of the hyperloop tube) can be covered in a day by truck. Thus, it would likely be more cost effective and still very quick delivery time (less than a day), to make the shipment by truck if the cargo is currently going truck.

3.1.3 Rail

Hyperloop would likely not cut into rail market share significantly. Freight rail service has the advantage when moving heavy, bulk cargo that is not time sensitive. With multiple high speed rail passenger lines in place all over the world, it is notable that although the idea of using the high speed lines for freight is sometimes discussed, it has not actually been pursued, outside of priority postal service which is in

decline because of the dominance of the internet. This observation suggests that there may not be need for very high speed ground transportation for freight.

3.1.4 Water

Because only air (expensive but fast) and ship (cheap but slow) are available for cargo shipment across water of distance that prohibits building a bridge, there is a compelling need for an additional mode. For cargo, the super-fast speeds are not of themselves the compelling feature of hyperloop, rather super-fast speeds enable higher throughput for a given tube size.

Recent presentations by HT have focused on putting the hyperloop tubes underwater as a way to avoid land acquisition costs for right of way. The HT presentations also mention the idea of using hyperloop to facilitate off-shore port facilities. Many ports are capacity constrained and unloading containers from ships to a hyperloop tube to be brought inland for sorting and distribution using equipment on offshore platforms could provide much needed expansion for port facilities.

4. System Costs

Upon publication in 2013, the low costs included in the “Hyperloop Alpha” white paper attracted a great deal of media attention. “Hyperloop Alpha” estimated a cost of \$6 billion for the passenger-only version system, less than one tenth of the cost for the California High Speed Rail (CAHSR), then estimated at \$68.4 billion.¹⁷ This section will investigate the capital and operating costs of the “Hyperloop Alpha” proposal, compare those costs with other modes of transportation, and discuss potential issues with the proposal’s cost estimates. For simplicity, the discussion will focus exclusively on the passenger-only version and exclude the passenger-plus-vehicle version.

4.1 Capital Costs

“Hyperloop Alpha” estimated the total construction cost of the system to be \$6 billion including guideway construction, capsule fabrication, and stations for a route from the Los Angeles metropolitan area to the San Francisco Bay, or \$17 million per mile.¹⁸ Subsequent to the Alpha white paper, HT gave a presentation citing \$25 -\$27 million per mile for just the technology, excluding land acquisition. For an approximate frame of reference, California HSR faces costs of \$63-\$65 million per mile and in Europe the cost is \$43 million per mile, although those figures include costs of land acquisition but exclude train sets. For an almost entirely underwater track specifically from Helsinki to Stockholm HT estimates a cost of \$64 million per mile including vehicles.¹⁹

Beyond construction costs, the full capital cost of an infrastructure project typically includes conceptual engineering, final design, environmental planning, and land acquisition. These professional costs are likely easier to estimate for existing technologies and generally exclude basic research and design costs needed to bring hyperloop technology to market. These costs are excluded from the construction estimate and are likely to be significant.

4.1.1 Comparison with Other Transportation Modes

As presented in “Hyperloop Alpha”, the construction costs of hyperloop’s fixed capital assets per mile of infrastructure are lower than the traditional high speed rail and substantially lower than the costs of a maglev system. Table 10 below shows the capital costs of various passenger transportation technologies both observed and proposed. One issue driving the idea that hyperloop would be lower cost to build than HSR is that by constructing an elevated system on pylons, the builder would just need to purchase

¹⁷ Hyperloop Alpha. Page 8.

¹⁸ Hyperloop Alpha. Page 56.

¹⁹ <https://hyperloop-one.com/blog/FS-Links-Hyperloop-One-Baltic-Sweden-Finland-Aland-Islands>

“air rights” which would be lower cost than outright land acquisition. Further, there is an assumption that the system could operate on the existing highway right-of-way further reducing costs. In addition, there appears to be an understanding that the tube guideway would be lighter weight than a steel wheel rail system and thus be cheaper to build. HSR and maglev could also be built on elevated tracks and on existing highway right-of-way. However, the relative cost savings from building a supposedly lighter-weight elevated system is an interesting future research question. Air appears to have a cost advantage because outside of airport facilities, no right of way is needed. Expanding capacity at airports is quite expensive, but those investments add huge increments of capacity and offer flexibility to reach a wide range of destinations.

Table 10. Comparison of Capital Costs by Transportation Mode.

Mode	Infrastructure Cost (per mile)	Note
High Speed Rail	CAHSR: \$63-65 million Europe: \$43 million ²⁰	CAHSR figure and Europe average from recently completed projects as detailed in the GAO report.
Maglev	Baltimore – Washington \$132 million	Completely separated guideway, ROW acquisition, station
Air	\$1.2 billion for 5 th runway in Atlanta (2006) ²¹ \$1.8 - \$3 Billion for additional runway Philadelphia ²²	While no right-of-way exists, airlines require substantial infrastructure at airports along with the air traffic control network.
Hyperloop	Alpha: \$17 million Hyperloop Technologies: \$25-27 million (minus land) \$64 million (underwater)	Based on the estimates presented in the Hyperloop Alpha proposal. HT estimate excludes land acquisition

²⁰ <http://www.gao.gov/new.items/d09317.pdf> Tables 2 & 3. Pages 23-24

²¹ <http://www.atlanta-airport.com/Airport/Construction/Fithrunway.aspx>

²² http://articles.philly.com/2012-01-09/news/30607749_1_new-runway-biggest-airline-philadelphia-international-airport

4.1.2 Low Cost Estimates

Hyperloop's cost estimates are lower than other modes, but as the technology is still conceptual and in very initial testing, there is uncertainty in both the underlying infrastructure needed to operate a system and the cost to construct it. Current proposals indicate the potential for more or larger tubes that would increase the overall construction cost. The costs presented above in the Table 10 comparison represent the floor of cost as presented in the "Hyperloop Alpha" proposal. However, critics have questioned validity of those cost estimates and suggest that the costs might be much higher than initially published.²³

This section will investigate the infrastructure components of the "Hyperloop Alpha" proposal and discuss any cost implications. While "Hyperloop Alpha" is but the initial proposal, its cost estimates are the most thorough and allow for investigation. The estimates of current private sector initiatives developing hyperloop technologies may differ from the "Hyperloop Alpha" proposal, but it offers a useful baseline for discussion.

Table 11 shows the cost per component of the 354.6 mile route described in the Hyperloop Alpha paper's passenger-only variant. It does not include the cost of the pods. The proposed route does not terminate at Los Angeles Union Station or San Francisco's Transbay Center, the planned endpoints of California High Speed Rail.

²³ Examples of press claiming high cost estimates:

http://bits.blogs.nytimes.com/2013/08/15/could-the-hyperloop-really-cost-6-billion-critics-say-no/?_r=0

<http://www.businessinsider.com/elon-musk-is-dead-wrong-about-the-cost-of-the-hyperloop-in-reality-it-would-be-100-billion-2013-8>

<http://greatergreaterwashington.org/post/19848/musks-hyperloop-math-doesnt-add-up/>

Table 11. Cost Estimate for Guideway in Hyperloop Alpha Proposal

Component	Cost (Million USD)	Note
Tube Construction	650	709.2 miles of Tube
Pylon Construction	2,550	25k pylons
Tunnel Construction	600	15.2 miles of tunnel
Propulsion	140	Linear induction motors
Solar Panels & Batteries	210	Panels cover both tubes
Station & Vacuum Pumps	260	2 stations @ \$125 m each
Permits & Land	1,000	Largely in I-5 ROW, minimal acquisitions
Total	5,410	

The cost estimates for individual line items may underestimate the total cost to construct a hyperloop system, beyond the exclusion of research and development funds to bring the technology from concept to market. The following list describes factors that may potentially increase the cost estimate for some line items but is not meant to substitute for a full civil engineering analysis to estimate costs.

Additionally, cost elements are subject to variation in material prices.

- **Tube Construction.** The tube is to be prefabricated offsite and positioned on the pylons. The cost estimate is based on two tubes roughly 3 meters in diameter. Increasing the number of tubes or the tube diameter would increase the total tube cost. Indeed, a 3 meter diameter tube for the Alpha estimate would not be large enough for standard 10 foot tall shipping container which shows how outdated these costs estimates are given that the firms presently active had announced they will focus on freight initially.
- **Pylon Construction.** 25,000 concrete pylons along the route. Pylon cost may increase if more tubes are added. One critique suggested that the pylons would need more robust seismic dampers than described in the proposal that would significantly raise costs.²⁴
- **Tunnel Construction.** The Hyperloop Alpha proposal estimated \$50 million per mile of tunnel. The cost estimate is based on two tubes roughly 3 meters in diameter. Increasing the number of tubes or the tube diameter would increase the tunnel cost per mile. Hyperloop Alpha estimates roughly 15 miles of total tunnel length but routing changes could change this figure.

²⁴ <https://www.quora.com/What-are-the-biggest-challenges-to-and-feasibility-of-Elon-Musks-Hyperloop>

- **Station & Vacuum Pumps.** Hyperloop Alpha estimated station construction costs at \$125 million. The conceptual station locations were outside the urban cores both in San Francisco and Los Angeles and stations construction would be more expensive in an urban location. If more tubes are added, station and vacuum pump costs would increase to handle greater capacity. Adding intermediate stations or alternate branches would similarly increase station costs.
- **Permits & Land.** Land costs have potential to be substantially higher than estimated by Hyperloop Alpha. The Alpha paper suggests that by building the system on pylons, land owners will be willing to sell overhead access and pylon rights for lower prices than is needed for a ground level high-speed rail system. However, HSR could also be built on pylons and project planners did not pursue that option, suggesting that such cost savings compared to ground level were not sufficient to overcome the additional complexities and costs of elevated construction for HSR. Hyperloop's lighter weight may mitigate the cost of pylons. Obtaining NEPA clearance and other permitting approvals will be a significant cost, particularly with a technology unfamiliar with federal agencies.

4.1.3 Missing Cost Components

A criticism of the Hyperloop Alpha proposal is that the route stops short of the California HSR endpoints and that a truly analogous system would be higher. In order to achieve ridership necessary to divert passengers from other modes and cover its capital costs, the route likely needs to continue into the urban core of both San Francisco and Los Angeles. At the northern end, the Hyperloop Alpha terminates in the East Bay but does not cross the San Francisco Bay into the city itself and the additional cost of bridging or tunneling under the Bay and into San Francisco would be substantial. As a point of comparison, New Jersey recently cancelled a similar two-track tunnel project under the Hudson River connecting New Jersey with New York City. The Access to the Region's Core tunnel project was budgeted at \$8.7 billion, with some projections as high as \$15 billion.²⁵ A hyperloop tunnel under the San Francisco Bay into the Transbay Center alone could exceed the proposed cost of the system.

At the southern end, expanding the route into Los Angeles Union Station would substantially increase the costs. Los Angeles is currently constructing a 2 mile rail tunnel connecting several rail lines near downtown at a cost of \$1.4 billion.²⁶ Los Angeles Union Station is located 25 miles further south than Hyperloop's proposed endpoint. A project combining even some tunneling or raised guideway for 25 additional miles in an expensive urban environment would be substantial.

Also missing from the proposal is any capsule maintenance facility where they would be cleaned, maintained, and repaired. The description of the station describes a small platform capable of handling only three to four capsules at a time eliminating their capability to store capsules for service and

²⁵ New Jersey ARC tunnel costs.

http://www.njtransit.com/tm/tm_servlet.srv?hdnPageAction=PressReleaseTo&PRESS_RELEASE_ID=2632

²⁶ <http://www.latimes.com/local/lanow/la-me-regional-connector-20151112-story.html>

inspection purposes. The cost of a maintenance facility would vary depending on the location and footprint of such a facility, however, using the estimated station cost as a proxy, each maintenance facility could cost \$125 million.

4.2 Operating Cost

The Hyperloop Alpha proposal offers no discussion or projection of operating & maintenance (O&M) costs apart from a single mention that its projected ridership and fare recovery covers daily operational costs with a \$20 fare. Assuming that Hyperloop's largest operating cost, energy, is fully covered by the self-sufficient solar panel system, there are still daily O&M costs that must be considered. This section presents several key O&M cost areas that would need to be added to any comprehensive analysis of high speed transportation options. These costs are largely labor and dependent on the size of the Hyperloop operator's staff, but might be estimated by looking at overhead rates for similarly sized companies.

4.2.1 Daily Management, Dispatching, & System Control

While the operation of the system itself is likely highly automated, some element of human control or supervision is needed from a central command center to address issues as they arise. Day to day system operation at a minimum includes dispatching, security, and maintenance. If this work does not take place at one of the stations, the capital cost of a dispatch facility would need to be added to the cost estimate.

4.2.2 Management and Planning

In addition to day to day system operation, general management is needed for strategic planning of the system, long term maintenance, personal management, IT services, and business development. If this work does not take place at one of the stations, the capital cost of a facility would need to be added to the cost estimate.

4.2.3 Stations

The operating cost of stations was not mentioned in the proposal. While the Hyperloop Alpha proposal describes an electronic-only ticketing system that would eliminate ticket sales agents, station operations likely require other staffing. Examples of station labor costs likely to be Hyperloop stations are station safety and security personnel, customer service, pod maintenance or cleaning, and customer baggage assistance. Additional, station costs will include utilities and water for restrooms, connections to other ground transportation, and other customer amenities (coffee, Wi-Fi, or bookstore). These station operation costs need to be added to the ongoing cost of operations.

4.2.4 Infrastructure Inspection

Given the speeds involved and the narrow tolerances permitted, any Hyperloop technology must have a rigorous inspection regime to maintain safe operations. Amtrak inspects its high speed tracks visually twice a week and using an automated track geometry inspection vehicle roughly every 30 days. Amtrak's track geometry car inspects the rails as part of normal service as the car is coupled to a train ensuring revenue operations generally aren't affected. Presumably an inspection pod will be created to inspect the interior of the tube at normal operating speed, but capital costs for an inspection pod need to be added to the cost estimate if it is not already integrated into each passenger pod.

Federal regulators will likely require an exterior inspection of the tubes & pylons be conducted at a much lower speed for periodic intervals on par with Amtrak's bi-weekly requirement. The cost for this inspection labor as well as any vehicles or equipment needed to inspect the tube (trucks, cherry picker lifts, and electronic equipment for solar testing) need to be added to any cost estimate.

4.2.5 Infrastructure Maintenance

No mention of maintenance costs were mentioned in the Hyperloop Alpha proposal, but components will inevitably fail and need repair. These costs will need to be added to any cost estimate but are not estimated here.

As mentioned above in Section 2.1.8, repairs within a tube will necessarily halt operations in that tube and depending on system redundancy may impact other tubes. Another large cost for any inspection and maintenance activity is the foregone revenue from any downtime if operations have to be halted. The redundancy of the system may impact its ability to continue revenue operations during a maintenance period.

5. Regulatory and Policy Issues

5.1 Access to Public Rights of Way (ROW)

Early discussions of hyperloop concept suggested that a hyperloop system could be built at lower cost than HSR by minimizing land acquisition costs through extensive use of highway medians and other public ROW. While it is not uncommon to use highway medians for other transport modes, such as light rail transit, this would raise numerous safety, engineering, and aesthetic issues. More broadly, state highway officials would need to consider whether the public interest is best served by this use. It is an open question as to whether communities would be willing to host a facility that services long distance travel mode at the expense of using resources to provide local transit. As mentioned in Section 2.1.9 discussing interoperability, as currently described, hyperloop guideway could only be used for hyperloop pods. It would be an interesting research question to evaluate whether the system could be adapted to offer lower speed transit-type service (with more stations accessed) within metropolitan areas. Such interoperability might make communities more willing to host the facilities and grant hyperloop access to city centers, instead of requiring the building of terminal stations at the outskirts of town.

5.2 Safety Regulation

Because Hyperloop is an entirely new system that runs on neither roads nor rails, it may present novel issues related to the Federal role in ensuring safe operation. For one, it is unclear which of the USDOT modal administrations, if any, would have the legal authority to issue and enforce safety regulations for hyperloop, and the extent to which safety responsibility would be shared with state regulators and private owners/operators. Emergency response across a 500-mile alignment would also need to be coordinated with state and local agencies. In particular, the proposed Hyperloop alignment passes through rural areas where local fire departments may not have the specialized equipment and expertise necessary to address a fire or evacuation of the elevated system. The Shanghai maglev system is also elevated so a similar concern may be present for that technology but HSR is generally not elevated,

5.3 Federal involvement with development of other modes

The United States Department of Transportation (USDOT) and its modal administrations have made significant investments in the US aviation system and in researching the feasibility of high-speed surface travel technologies, notably high-speed rail (HSR) and maglev.

The Federal government has supported commercial aviation since at least 1925, with the passage of the Air Mail Act, which provided an important source of revenue to the nascent aviation industry in the form of Post Office contracts. During the 1930s the Federal government also took on responsibility for air

traffic control functions. The World War II military buildup saw massive investment in airfields and other infrastructure, followed by significant technology transfer from the defense industry to civilian aviation in areas such as aircraft design. Today, Federal investment in aviation continues through the Airport and Airway Trust Fund, supported in part by ticket and fuel taxes, which funds FAA operations, upgrades to air traffic control, and grants to local airports.

Federal support for HSR dates back to the High Speed Ground Transportation Act of 1965, (\$90 million for R&D, or about \$671 million in today's money). Specific HSR corridors were first designated in the Intermodal Surface Transportation Efficiency Act (ISTEA) legislation in 1992, with additional corridors designated in 1998-2004. Major funding support resumed in 2008-2009 with the Passenger Rail Investment and Improvement Act (PRIIA) and American Recovery and Reinvestment Act (ARRA), which together led to a renewed emphasis on HSR corridor development and a total of \$10 billion in funding for state- and region-led projects. Since then, there has been planning support, and about \$3.2 billion in funding for incremental improvements and Positive Train Control on designated HSR corridors. However, it is unclear whether significant Federal investment in HSR will continue, due largely to political concerns about cost, cost-effectiveness, and subsidy levels; a more constrained fiscal climate vis-à-vis the stimulus package era; and arguably, the lack of a high-profile HSR success story outside of the highly urbanized Northeast Corridor.

Magnetic levitation (maglev) trains have also received substantial federal research support, starting with a National Maglev Initiative (NMI) authorized in 1991 with \$12 million in funding. NMI studies on maglev technologies, performance, safety and environmental issues, and cost concluded that US maglev applications were premature. However, the Transportation Equity Act for the 21st Century (TEA-21) established the Federal Railroad Administration (FRA)'s Maglev Deployment Program to explore the feasibility of maglev technology on specific routes, awarding grants to 7 projects for pre-construction planning and environmental studies. Two finalists were selected for continued evaluation and initial project development, including engineering design and analysis. However, funding has been limited since then and FRA has generally not pursued the maglev concept. In the United States, maglev implementation appears to suffer from high capital costs (including right of way acquisition, guideway, and power infrastructure construction), lack of interoperability with existing rail infrastructure, and modest travel time and cost savings versus commercial air service. To date, technical and commercial viability has been proven in overseas deployments; the most ambitious is the Japan Central Railroad Tokyo-Osaka route, set to open in 2027.

5.4 Public Funding

It seems clear that even if hyperloop has capital costs lower than HSR, it will still need public subsidy. At present, there appears to be a general presumption against government interfering in the private marketplace or placing large "bets" on particular new technologies or products, at least in the US. For that reason, the various hyperloop companies appear to be focusing on foreign markets.

For the hyperloop concept, the relevant public funding policy question would be whether the prospect of very high-speed, potentially low-emissions travel in a limited number of corridors would be so compelling as to warrant public funding; and if so, at what stage of development? If significant public investment were to occur, that would also introduce myriad questions about governance, business model, and fare policy, since the system would not be fully private.

In the US, Federal funding comes with many stipulations about how it can be used including Davis-Bacon Act prevailing wages and Buy America provisions. The Buy America requirements apparently halted progress on the DesertXpress proposal for HSR between Victorville, CA and Las Vegas. There may also be equity considerations, particularly if the hyperloop emerges as a high-end, niche product for passengers willing to pay a substantial premium for travel time savings. As regards freight, after deregulation in the 1970s and 1980s of the air, rail and trucking sectors, the US freight policy has been to generally leave those markets to the private sector.

6. Safety Issues

The purpose of this safety analysis is not to conduct a formal safety risk assessment in which hazards are identified, the risk of possible outcomes of the hazards in terms of severity and likelihood of occurrence is determined, and measures to mitigate the risk are proposed. The intent is merely to outline some of the safety issues that need to be addressed during the design, development, and requirements definition phases of the Hyperloop transportation concept. These safety issues and considerations have been documented in white papers describing the Hyperloop concept published by Elon Musk of SpaceX²⁷ and Hyperloop Transportation Technologies²⁸, as well as in numerous publicly-available articles and critiques. What is lacking in the currently available literature, however, are detailed descriptions of safety mishaps and the failure chains leading to them for capsules, passengers, and system operation, along with credible prevention options and mitigation strategies. Musk advances several strategies and design solutions for mitigating the risks of potential safety hazards in his Hyperloop Alpha White Paper, and many of these are included in this section.

6.1 Key Safety Questions

Hyperloop Transportation Technologies has listed several questions that have important safety-related implications for the Hyperloop concept. Many of these questions will be discussed briefly in the sections that follow.

- How will tube construction allow for emergencies, such as rapid depressurization or large-scale leaks, capsule malfunction, or natural disasters such as earthquakes?
- What will happen in the event of the depressurization of a Hyperloop capsule?
- What happens if a capsule is stranded in the tube? Where will the emergency exits be?
- How fast can the capsule decelerate for emergency stop without damaging the system?
- What is the capsule behavior if it hits higher or even normal density air while traveling at 700 MPH? Can it be designed to survive that and protect the passengers? How fast will the capsule decelerate if it encounters high-density air?
- Can the problem of excessive drag on the capsules be overcome even in such a thin atmospheric environment? What is the potential of supersonic air surrounding the capsules?

²⁷ Hyperloop Alpha

²⁸ Hyperloop Transportation Technologies Crowdstorm Documentation

- If there is a large tube breach, will the air be filling the tube at a high velocity? Will the additional speed and turbulence increase the danger to the capsule? Will oxygen masks work in a major capsule breach?
- How long will the system continue to run if power is lost in the area?
- Is it possible to provide a fire suppression system inside the capsule?
- What material and method of tube construction presents the ideal combination of safety, cost, and overall function (e.g., steel, carbon fiber, Kevlar)?

6.2 Onboard Passenger Emergency and Passenger Evacuation

In the event of a serious incident, passengers may lose oxygen. In such a circumstance, as in airplanes, oxygen masks would be deployed. Once the capsule reached the destination safely it would be removed from service. Safety of the onboard air supply in hyperloop would be very similar to aircraft. All capsules would have direct radio contact with station operators in case of emergencies, allowing passengers to report any incident, to request help and to receive assistance. In addition, all capsules would be equipped with first aid equipment. Despite these safety measures, the issue of an en route passenger illness or emergency is not addressed rigorously in the available literature. SpaceX claims that because of the short hyperloop travel times (San Francisco to Los Angeles in 30 minutes), the best course of action in case of emergency would be for the capsule to communicate the situation to the station operator and for the capsule to finish the journey in a few minutes where emergency services would be waiting to assist. All capsules would have direct radio contact with station operators in case of emergencies, allowing passengers to report any incident, to request help and to receive assistance. In addition, all capsules would be fitted with first aid equipment. Musk concludes that an emergency in a hyperloop capsule simply requires the system to complete the planned journey and meet emergency personnel at the destination.²⁹

Emergency evacuations also present a safety challenge. Musk discusses the use of escape hatches, but these would likely create undue leakage. One critique of hyperloop³⁰ states that the larger version of hyperloop (intended to carry cars as well as passengers) may accommodate these needs, but the proposed passenger-only version did not.

²⁹ Hyperloop Alpha, p. 54

³⁰ Natalie Burkhard, “Why Invent the Hyperloop?”, <http://large.stanford.edu/courses/2014/ph240/burkhard2/>

6.3 Capsule Deceleration in Response to System Malfunction

The passenger capsules, which coast through the tubes, pushed in front of a column of pressurized air, are coasting for much of their journey. They would be equipped with emergency brakes and engine-driven wheels in case they are stranded or need to avoid hitting a stranded hyperloop pod. In the event of a large scale capsule depressurization, other capsules in the tube would automatically begin emergency braking while the hyperloop tube would undergo rapid re-pressurization along its entire length.

In one proposed operational concept, once all capsules behind the stranded capsule are safely brought to rest, capsules would drive themselves to safety using small onboard electric motors to power deployed wheels. All capsules would be equipped with a reserve air supply great enough to ensure the safety of all passengers for a worst case scenario event.

The safety concern in the case of a required rapid deceleration is that the margin for error appears to be relatively slim. The system would have up to 28-passenger cars departing every two minutes on average or every 30 seconds during peak-use periods, putting as many as 70 capsules in a tube connecting Los Angeles to San Francisco and more than twice that number on a 1,000-mile route. Given their speeds and departure intervals, the capsules would be separated by appreciable distances, approximately 37 km (23 miles) on average during operation. Nevertheless, a serious safety hazard is introduced if a problem occurs that forces the capsules to slow or come to a stop and the brakes fail in even one of the capsules.³¹

NASA calculated required stopping distances in the event of an emergency of system failure or malfunction. To simplify the calculations, a maximum capsule speed of 295 m/s (660 mph), maximum acceleration of 0.5 g's, and a capsule launched every 30 seconds were assumed. In addition, it was assumed that each capsule would know instantly if a capsule ahead has emergency stopped. A capsule can accelerate to its maximum speed of 295 m/s in 60 seconds. Using these assumptions, the calculations indicated that, even if the first capsule goes from maximum speed to stopped instantaneously, the second capsule only needs to decelerate at 0.5 g to avoid collision (with 0% factor of safety), or it can decelerate at 0.6 g with a 20% factor of safety. From these results, it was determined that the separation distance between two capsules once they both reach maximum speed will be approximately 8.85 km, and approximately 4.5km would be needed to come to a complete stop from maximum speed at 1 g deceleration. Thus, the analysis concluded that the proposed 30-second headway is very feasible from a stopping time perspective.

³¹ Matt Peckham, "4 Reasons Elon Musk's Hyperloop Could Tank," <http://techland.time.com/2013/08/13/4-reasons-elon-musks-hyperloop-could-tank/>

6.4 Power Outage

While hyperloop would include safety systems, from oxygen masks (in the event of depressurization) to emergency brakes and retractable wheels in each pod, systems like these are not impervious to glitches, power outages, and battery backup failures. In the event of a power outage in the area, and to avoid a lengthy shutdown of the Hyperloop system, it seems that it would be necessary to at least complete the trip for all in-progress capsules. Hyperloop Transportation Technologies states that it would be desirable, if possible, to continue for 8 hours to allow people to get home.

SpaceX maintains that the vast majority of the hyperloop travel distance is spent coasting and so the capsule does not require continuous power to travel. The risk of a power outage is mitigated in their design by using two or more redundant lithium ion battery packs to power the capsule life support systems. In the event of a power outage occurring after a capsule had been launched, all linear accelerators would be equipped with enough energy storage to bring all capsules currently in the hyperloop tube safely to a stop at their destination. In addition, linear accelerators using the same storage would complete the acceleration of all capsules currently in the tube. For additional redundancy, all hyperloop capsules would be fitted with a mechanical braking system to bring capsules safely to a stop.³²

6.5 Capsule Depressurization

One potential risk for passengers of trains operating in evacuated tubes is that they could be exposed to the risk of cabin depressurization unless safety monitoring systems can re-pressurize the tube in the event of a train malfunction or accident. However, since the hyperloop capsules operate very close to the Earth's surface, emergency restoration of ambient pressure should be straightforward. In the event of a minor leak, it is proposed that the onboard environmental control system would maintain capsule pressure using the reserve air carried onboard for the short period of time it will take to reach the destination. In the case of a more significant depressurization, oxygen masks would be deployed as in airplanes.

Pressure is so low (100 Pascal) that under the point of view of human physiology the conditions are closer to space than to the ones at commercial airplanes. At 100 Pascal, none of the emergency measures commonly used even by military pilots (except the partial pressure suit), are enough to avoid severe hypoxia and traumas related to the decompression.³³

Maintaining even a partial vacuum is nontrivial and expensive. If a leak were to occur, the entire tube

³² Hyperloop Alpha, p. 54

³³ Hyperloop Transportation Technologies Crowdstorm Documentation

would shut down. In addition, the extremely thin air cushion is worrisome. The tolerances provide little factor of safety so that in the best case scenario, the passengers experience uncomfortable bumps and turbulence; the worst case outcome could be potentially devastating.³⁴

6.6 Capsule Stranded in Tube

A capsule stranded in a tube due to a system or component malfunction or perhaps a passenger emergency presents a safety hazard. In their Hyperloop Alpha White Paper³⁵, SpaceX addresses this issue by stating that this scenario is highly unlikely since the capsule coasts the majority of the distance at high speed, and no propulsion is required for more than 90% of the journey. If a capsule were somehow to become stranded, capsules ahead would continue their journeys to the destination unaffected. Capsules behind the stranded one would be automatically instructed to deploy their emergency mechanical braking systems. Once all capsules behind the stranded capsule had been safely brought to rest, capsules would drive themselves to safety using small onboard electric motors to power deployed wheels. In addition, all capsules would be equipped with a reserve air supply great enough to ensure the safety of all passengers for a worst case scenario event.

6.7 Environmental Hazards

An important safety concern, particularly on the proposed route from Los Angeles to San Francisco through central California, is resistance of the pylon and tube infrastructure to earthquakes. In California, transport systems are all built with earthquakes in mind. Musk comments that hyperloop would be no different with the entire tube length built with the necessary flexibility to withstand the earthquake motions while maintaining the hyperloop tube alignment. It is also likely that in the event of a severe earthquake, hyperloop capsules would be remotely commanded to actuate their mechanical emergency braking systems.³⁶

Another concern expressed in one critique of the hyperloop concept has to do with temperature. It is argued that the passenger capsule will be compressing air and expelling it downwards and backwards, thus creating an enormous amount of heat that could potentially damage the capsule and its machinery.³⁷ Musk's solution is to add to each capsule a water tank that will capture that heat and turn

³⁴ Natalie Burkhard, "Why Invent the Hyperloop?", <http://large.stanford.edu/courses/2014/ph240/burkhard2/>

³⁵ Hyperloop Alpha, p. 55

³⁶ Hyperloop Alpha, p. 55

³⁷ Matt Peckham, "4 Reasons Elon Musk's Hyperloop Could Tank," <http://techland.time.com/2013/08/13/4-reasons-elon-musks-hyperloop-could-tank/>

it into steam to be offloaded at the next station. However, a thermodynamic analysis conducted by NASA³⁸ concluded that the dominant heating factors and thermal interactions are a result of the massive tube structure and are unrelated to the heat generated by the capsule compression system. Therefore, the temperature effect from air compression would be minimal and the steady-state temperature inside the tube would be only 10-20°F higher than ambient temperatures. As a result, the need for the originally proposed water-based heat exchangers is eliminated.

Wind stress is another challenge. Any structure elevated 100 feet off the ground is going to be under a lot of wind pressure, which will act on it in unpredictable and sometimes multiple directions. If that structure is a heavy tube stretching hundreds of miles in either direction, you effectively have a big sail. Will the concrete pylons be powerful enough to resist that pressure? This problem is similar to air flow over a cylinder and could therefore be easily and accurately modeled.

6.8 Prototype

The biggest issues with hyperloop technology are speed and scale. It is still unclear how to create a prototype that verifies the safety of the technology and allows testing of all necessary components. It is easy to imagine safety concerns limiting hyperloop speeds to just a fraction of its theoretical top speed or right-of-way issues keeping stations far from urban centers. These deployment details are critical issues for the hyperloop, but as long as the tests are focused on the planned 5-mile test tracks that are under development, it is not clear these issues will ever be fully understood. If one wonders how fast the hyperloop can go or how safe it will be at high speeds, a 5-mile test track will only provide the slightest glimpse of the important challenges ahead. A test track of only 5 miles falls far short of the distance needed to reach 700 miles per hour. For the same reason, these test tracks cannot address the unique safety issues that come with near-supersonic travel. The result is just a tube-powered version of conventional transportation technology such as maglev and high-speed rail.³⁹

A possible solution proposed by Hyperloop Transportation Technologies would be to create a full-scale version on a commercial route used for freight transport only. Using this approach, all components of the system could be tested under optimized speed and acceleration conditions, and valuable data would be collected for the final design of system used to transport human passengers. In order to get up to speed and be able to slow down, a minimum length of a little over 38 km (23.61 miles) would be needed, but it would not be able to be used by people; a smooth ride would require approximately 120km (74.56 miles). As the cost for such a prototype is close to the cost of a fully operational system, it

³⁸ Chin, J. C., Gray, J. S., Jones, S. M., and Berton, J. J. "Open-Source Conceptual Sizing Models for the Hyperloop Passenger Pod." AIAA 2015-1587, 56th AIAA/ASCE/AHS/ASC Structural Dynamics and Materials Conference, January 2015.

³⁹ Russell Brandom, "The Hyperloop's biggest questions are still unanswered," <http://www.theverge.com/2015/6/16/8789061/hyperloop-test-track-problems-elon-musk-spacex>

would make sense to place it in an area that has an actual need for hyperloop transportation.

7. Key Research Issues

In attempting to evaluate the commercial feasibility of the hyperloop transportation concept, several interesting research questions have emerged:

1. Is the hyperloop transportation system sufficiently lightweight that there would significant construction cost savings compared to building an elevated HSR or maglev system?
2. What are the technology hurdles to building hyperloop underwater and can they be overcome?
3. Can the capacity of a hyperloop pod be expanded to seat more than the originally proposed 28 passengers?
4. What would be the weight limit for a freight capsule?
5. How big would the tube need to be in order to carry a standard size shipping container?
6. Can the system be designed so that in addition to carrying long distance passengers, it can also provide local transit service?
7. Would hyperloop be loud for passengers? Would hyperloop be loud in communities?

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